Mixing and CP violation in charm decays

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Motivation

The peculiarities of charm physics

- Many challenges …
  - The charm quark is not that heavy $\alpha_s(m_c) \sim 0.33$ $\frac{\Lambda_{\rm QCD}}{m_c} \sim 0.30$
  - CP violation effects are small due to CKM
  - There are pronounced GIM cancellations $m_b, m_s, m_d \ll m_W$
- … which are also opportunities
  - Great possibility to test our understanding of QCD
  - High sensitivity to NP effects see talk by H. Gisbert
- Also, only system to study mixing in the up-sector

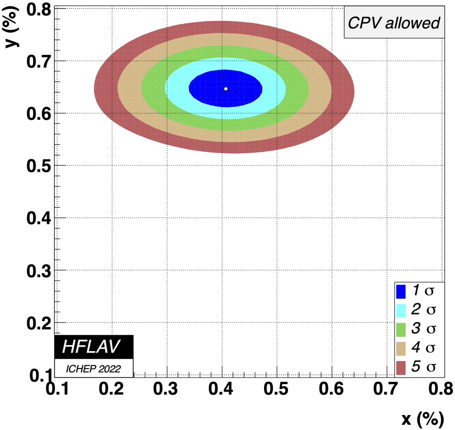
Complementarity to K- and B-mixing

see talks by E. Stamou and E. Malami

The experimental progress

- Experimental precision significantly improving
- Theoretical predictions not yet competitive
- Many more data expected

LHCb, Belle II, BESIII

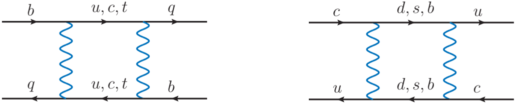


Need equal progress in theory to exploit the many experimental results

Theory of mixing

Meson mixing

- Neutral mesons mix with their antiparticles via box diagrams



- Evolution described by 2 × 2 Hamiltonian matrix

$$i\frac{d}{dt}\begin{pmatrix}|\mathcal{M}^0(t)\rangle \\ |\overline{\mathcal{M}}^0(t)\rangle\end{pmatrix} = \left(\hat{M} - i\frac{\hat{\Gamma}}{2}\right)\begin{pmatrix}|\mathcal{M}^0(t)\rangle \\ |\overline{\mathcal{M}}^0(t)\rangle\end{pmatrix} \Rightarrow \begin{cases}|\mathcal{M}_L\rangle = p\,|\mathcal{M}^0\rangle + q\,|\overline{\mathcal{M}}^0\rangle \\ |\mathcal{M}_H\rangle = p\,|\mathcal{M}^0\rangle - q\,|\overline{\mathcal{M}}^0\rangle\end{cases}$$

- Define mixing observables

$$\Delta M = M_H - M_L \qquad \Delta\Gamma = \Gamma_L - \Gamma_H$$

- And the dimensionless ratios

$$x = \Delta M/\Gamma \qquad y = \Delta\Gamma/2\Gamma \qquad \text{with} \qquad \Gamma = (\Gamma_H + \Gamma_L)/2$$

Meson mixing

- Theoretically, determine mixing observables as

see e.g. reviews [Artuso, Borissov, Lenz '15; Lenz, Wilkinson '20]

$$\Delta M \approx 2|M_{12}| \qquad \Delta\Gamma \approx 2|\Gamma_{12}| \qquad \phi_{12} = \arg\left(-M_{12}/\Gamma_{12}\right)$$

Expanding in the small parameters $|\Gamma_{12}|/|M_{12}|$ and/or ϕ_{12}

- M_{12} corresponds to dispersive part of $\mathcal{M}^0 \to \overline{\mathcal{M}}^0$ amplitude

Directly sensitive to heavy NP particles

- Γ_{12} corresponds to absorptive part of $\mathcal{M}^0 \to \overline{\mathcal{M}}^0$ amplitude

Directly sensitive to light NP particles

- CP violation in mixing encoded in parameter a_{fs}

$$\left|\frac{q}{p}\right| \approx 1 - \frac{a_{\text{fs}}}{2} \qquad a_{\text{fs}} = \left|\frac{\Gamma_{12}}{M_{12}}\right| \sin\phi_{12}$$

B-mixing

- Off-shell contributions to box diagrams

$$M_{12} = \lambda_u^2\left(M_{cc} - 2M_{uc} + M_{uu}\right) + 2\lambda_u\lambda_t\left(M_{cc} - M_{uc} + M_{ut} - M_{ct}\right) + \lambda_t^2\left(M_{cc} - 2M_{ct} + M_{tt}\right)$$

  - Described in terms of $\Delta B = 2$ effective Hamiltonian

- On-shell contributions to box diagrams

$$\Gamma_{12} = \lambda_u^2\left(\Gamma_{cc} - 2\Gamma_{uc} + \Gamma_{uu}\right) + 2\lambda_u\lambda_t\left(\Gamma_{cc} - \Gamma_{uc}\right) + \lambda_t^2\,\Gamma_{cc}$$

  - Described by double insertion of $\Delta B = 1$ effective Hamiltonian

Can be computed within the HQE

$\lambda_u^d \sim \lambda_c^d \sim \lambda_t^d$ $\quad$ $\lambda_u^s \ll \lambda_c^s \sim \lambda_t^s$ $\quad$ $\lambda_x^q = V_{xb}V_{xq}^*$

- GIM and CKM suppressions go in the same direction

D-mixing

◇ Strong interplay of CKM and GIM suppression!

$\lambda_d \sim \lambda_s \sim \lambda \gg \lambda_b \sim \lambda^5$ $\lambda_x = V_{cx} V_{ux}^*$

$$M_{12} = \lambda_s^2 \left(M_{ss} - 2M_{ds} + M_{dd} \right) + 2\lambda_s \lambda_b \left(M_{bs} - M_{bd} + M_{dd} - M_{sd} \right) + \lambda_b^2 \left(M_{bb} - 2M_{bd} + M_{dd} \right)$$

$$\Gamma_{12} = -\lambda_s^2 \left(\Gamma_{ss} - 2\Gamma_{ds} + \Gamma_{dd} \right) + 2\lambda_s \lambda_b \left(\Gamma_{sd} - \Gamma_{dd} \right) - \lambda_b^2 \, \Gamma_{dd}$$

- ⋆ All terms are of similar size, pronounced cancellations
- ⋆ Dominated by double insertion of $\Delta C = 1$ effective Hamiltonian
  - ⋆ Can be computed within the HQE?

The HQE works for charm decays?

The HQE

- Powerful framework for inclusive decay widths of heavy hadrons

[Shifman, Voloshin '85]

$$\Gamma(H_Q) = \frac{1}{2m_{H_Q}} \mathrm{Im}\, \langle H_Q | i \int d^4x\, \mathrm{T}\Big\{ \mathcal{H}_{eff}(x)\, , \mathcal{H}_{eff}(0) \Big\} | H_Q \rangle$$

- Obtain systematic expansion see also e.g. review [Lenz '14]

$$\Gamma(H_Q) = \underbrace{\Gamma_3}_{\Gamma(Q)} + \underbrace{\Gamma_5 \frac{\langle \mathcal{O}_5 \rangle}{m_Q^2} + \Gamma_6 \frac{\langle \mathcal{O}_6 \rangle}{m_Q^3} + \ldots + 16\pi^2 \left[\tilde{\Gamma}_6 \frac{\langle \tilde{\mathcal{O}}_6 \rangle}{m_Q^3} + \tilde{\Gamma}_7 \frac{\langle \tilde{\mathcal{O}}_7 \rangle}{m_Q^4} + \ldots \right]}_{\delta\Gamma(H_Q)}$$

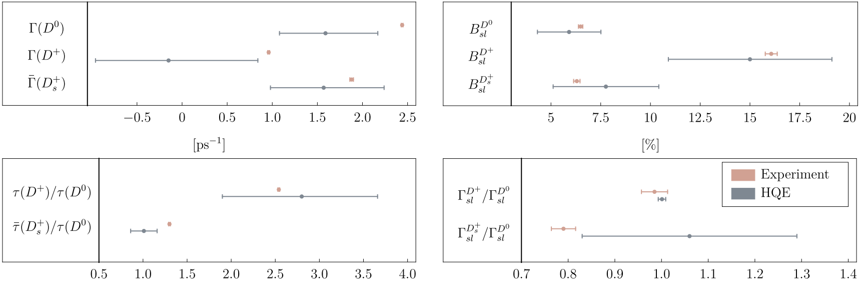
- Validity based on the assumption of $m_Q \gg \Lambda_{\mathrm{QCD}}$

- Successfully predicts beauty hadron lifetimes and B-mixing

[Lenz, MLP, Rusov '22; Gratrex, Lenz, Melić, Nišandžić, MLP, Rusov '23; Cheng, Liu '23]

[Lenz, Tetlalmatzi-Xolocotzi '19; Gerlach, Nierste, Shtabovenko, Steinhauser '22]

Charmed hadron lifetimes



[King, Lenz, MLP, Rauh, Rusov, Vlahos ’21]

- ◇ HQE can accomodate observed pattern in D-system
- ◇ Uncertainties still very large

Mainly due to charm mass and non-perturbative inputs

- ◇ Results confirmed by recent analyses, studied also baryons

[Gratrex, Melić, Nišandžić ’22; Dulibič, Gratrex, Melić, Nišandžić ’23]

Back to mixing in the charm sector

D-mixing

- ◇ Experimentally both x and y are measured quite precisely

[HFLAV '22]

$$x^{\text{exp.}} = (0.407 \pm 0.044)\,\% \qquad y^{\text{exp.}} = (0.647 \pm 0.024)\,\%$$

- ◇ Determine Γ_{12} within the HQE

$$\Gamma_{12} = 16\pi^2 \left[\tilde{\Gamma}_6 \frac{\langle \tilde{Q}_6 \rangle}{m_c^3} + \tilde{\Gamma}_7 \frac{\langle \tilde{Q}_7 \rangle}{m_c^4} + \ldots \right]$$

$\tilde{\Gamma}_6^{(2)\dagger}$	Gerlach, Nierste, Stabovenko, Steinhauser '22 Asatrian, Hovhannisyan, Nierste, Yeghiazaryan '17
$\tilde{\Gamma}_6^{(1)}$	Beneke, Buchalla, Greub, Lenz, Nierste '98 Beneke, Buchalla, Lenz, Nierste '03 Ciuchini, Franco, Lubicz, Mescia, Tarantino '03 Lenz, Nierste '06
$\tilde{\Gamma}_7^{(0)}$	Beneke, Buchalla, Dunietz '96 Dighe, Hürth, Kim, Yoshikawa '01

$\langle \tilde{Q}_6 \rangle$	1706.04622 ★ Kirk, Lenz, Rauh '17 ★
$\langle \tilde{Q}_7 \rangle$	VIA‡

★ HQET SR ★ Fermilab/MILC

† not yet included

‡ see also HPQCD 1910.00970

A long-standing puzzle

- Predictions of y based on the HQE are completely off

$$y^{\text{HQE}} \sim 10^{-4}\, y^{\text{exp.}}$$

- Failure of HQE for charm mixing?
  - Potential large impact of higher dimensional operators
    [Georgi '92; Ohl et al. '93; Bigi, Uraltsev '00]
  - Different renormalisation scale setting can lift GIM cancellations
    [Lenz, MLP, Vlahos '20]
- Alternatively, use exclusive approach
  - Estimate phase space effects for y, use dispersion relations for x
    see e.g. [Falk et al. '01; Falk et al. '04]
  - Obtain values of x and y closer to experimental data
- First steps taken towards future insights from lattice QCD
  [Hansen, Sharpe '12]

Alternative scale setting

- Consider the dependence of Γ_{12} on renormalisation scale $\mu_1^{q_1 q_2}$

$$\Gamma_{12} = \sum_{q_1 q_2 = ss, ds, dd} \tilde{\Gamma}_6^{q_1 q_2}(\mu_1^{q_1 q_2}, \mu_2^{q_1 q_2}) \langle \tilde{Q}_6 \rangle (\mu_2^{q_1 q_2}) \frac{1}{m_c^3} + \dots$$

- $\Gamma_{ss}, \Gamma_{dd}, \Gamma_{ds}$ contribute to different decay channels
  - Rescattering effects can only relate Γ_{dd} and Γ_{ss}

- Compute Γ_{12} varying $\mu_1^{ss}, \mu_1^{dd}, \mu_1^{ds}$ independently

$$\Omega \equiv \frac{2|\Gamma_{12}|^{\text{HQE}}}{\Delta\Gamma_D^{\text{exp.}}} \in [4.6 \times 10^{-5}, 1.3]$$

[Lenz, MLP, Vlahos '20]

CP violation in the charm sector

The experimental status

- Discovery of CP violation in D^0 decays by LHCb [arXiv:1903.08726]

$$\Delta A_{\mathrm{CP}} \equiv A_{\mathrm{CP}}(K^-K^+) - A_{\mathrm{CP}}(\pi^-\pi^+) = (-15.4 \pm 2.9) \times 10^{-4}$$

$$\Delta a_{\mathrm{CP}}^{\mathrm{dir.}} = (-15.7 \pm 2.9) \times 10^{-4}$$

- New data by LHCb on $A_{\mathrm{CP}}(K^-K^+)$ see talk by D. Mitzel
    - Combination with ΔA_{CP} gives [arXiv: 2209.03179]

$$a_{\mathrm{CP}}^{\mathrm{dir.}}(K^-K^+) = (7.7 \pm 5.7) \times 10^{-4} \qquad a_{\mathrm{CP}}^{\mathrm{dir.}}(\pi^-\pi^+) = (23.2 \pm 6.1) \times 10^{-4}$$

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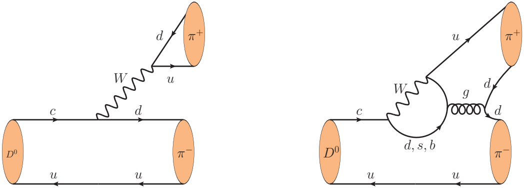
    - First evidence for direct CP violation in specific D^0 decay

The decay $D^0 \to \pi^-\pi^+$ *(and similarly for* $D^0 \to K^-K^+$*)*



- Theoretically very difficult, different topologies contribute

$$\mathcal{A}(D^0 \to \pi^-\pi^+) = \lambda_d(A_{tree} + A^d_{peng.}) + \lambda_s A^s_{peng.} + \lambda_b A^b_{peng.}$$

- From unitarity of CKM

$$\mathcal{A}(D^0 \to \pi^-\pi^+) = \frac{G_F}{2}\lambda_d T\left(1 + \frac{\lambda_b}{\lambda_d}\frac{P}{T}\right)$$

- Branching fraction mostly sensitive to T due to $\lambda_b/\lambda_d \sim \lambda^4 \ll 1$

Direct CP violation

- The direct CP asymmetry becomes

$$a_{\mathrm{CP}}^{\mathrm{dir.}}(\pi^-\pi^+) \equiv \frac{\Gamma(\overline{D}^0 \to \pi^+\pi^-) - \Gamma(D^0 \to \pi^-\pi^+)}{\Gamma(\overline{D}^0 \to \pi^+\pi^-) + \Gamma(D^0 \to \pi^-\pi^+)} \approx \underbrace{-13 \times 10^{-4}}_{-2|\lambda_b/\lambda_d|\sin\gamma} \left|\frac{P}{T}\right| \sin\phi$$

  - ⋆ Sensitive to difference of weak and strong phases γ, ϕ, and to $|P/T|$

- Similarly for $a_{\mathrm{CP}}^{\mathrm{dir.}}(K^-K^+)$, but with opposite sign due to $\lambda_s \approx -\lambda_d$

$$\Delta a_{\mathrm{CP}}^{\mathrm{dir.}} \approx 13 \times 10^{-4} \left(\left|\frac{P}{T}\right|_{K^-K^+} \sin\phi_{K^-K^+} + \left|\frac{P}{T}\right|_{\pi^-\pi^+} \sin\phi_{\pi^-\pi^+} \right)$$

- From naive estimates $|P/T| \sim 0.1$

$$|\Delta a_{\mathrm{CP}}^{\mathrm{dir.}}| \leq 2.6 \times 10^{-4}$$

No theory consensus yet

- Determinations within LCSRs confirm naive expectations

  [Khodjamirian, Petrov '17]

  - Triggered NP interpretations

    e.g. [Chala, Lenz, Rusov, Scholtz '19; Dery, Nir '19; Bause, Gisbert, Golz, Hiller '20]

- Potential explanations of ΔA_{CP} within the SM

  - Using U-spin relations and $\mathrm{SU}(3)_F$ symmetry e.g. [Grossman, Schacht '19]

    However, opposite sign for CP asymmetries, "U-spin anomaly"

    e.g. [Bause, Gisbert, Hiller et al. '22; Schacht '23], see also talk by T. Höhne

  - From analyses of topological amplitudes, or final state interactions

    e.g. [Li, Lü, Yu '19; Cheng, Chiang '19; Bediaga, Frederico, Megahlães '22]

- Recent study of rescattering effects using dispersive methods

  - Predictions of CP violation still below the experimental values

    [Pich, Solomonidi, Vale Silva '23]

Non-leptonic decays are challenging

- Tree-level decays like $\bar{B}_s \to D_s^+ \pi^-$ are theoretically “cleaner”

- Tensions between QCDF predictions and data ranging $(2-7)\sigma$

  [Bordone, Gubernari, Huber, Jung, van Dyk ’20]

  - QED corrections? Rescattering effects?

    [Beneke, Böer, Finauri, Vos ’21; Endo, Iguro, Mishima ’21]

  - Investigated potential BSM scenarios

    e.g. [Iguro, Kithara ’20; Cai, Deng, Li, Yang ’21; Fleischer, Malami ’21]

  - Interplay with collider constraints [Bordone, Greljo, Marzocca ’21]

- Discrepancies might be due to underestimated hadronic effects

  - Alternative determination entirely within LCSRs

    [MLP, Rusov (to appear soon)]

Conclusions

- Charm physics is a vibrant field, high potential for NP searches
- Precise theoretical predictions are currently challenging
    - Many tools are already available, improvements are doable!
- D-mixing puzzle still on-going
    - New insights gained on how to improve HQE predictions

Higher order perturbative and power corrections needed!

- No theory consensus yet on interpretation of $\Delta A_{\rm CP}^{\rm dir.}$
    - Less likely that new results on $a_{\rm CP}^{\rm dir.}$ can be accommodated in SM
- Experimental input fundamental to trigger interest

More, and more precise data crucial to guide the theory community

CHARM 2023 in Siegen, from 11-17 July

Physik im Apollo

Dienstag, 18.7.2023, Apollo Theater Siegen
Eintritt frei

Ab 17:00 im Foyer: Vorstellung der Arbeitsgruppen des Physik Departments der Universität Siegen
Ab 19:00 Grußwort von Bürgermeister Steffen Mues

Der Dunklen Materie auf der Spur

Abendvortrag von Prof. Dr. Matthias Neubert (PRISMA$^+$ Cluster of Excellence, Mainz)

Interstellar - Time: Alexander Breitenbach und Eleftheria Malami (Piano und Gesang)
Nothing else Matters: formafortis (Akrobatik), Piano

`https://indico.tp.nt.uni-siegen.de/event/1/`

Thanks for the attention